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# Contribution to the Performance Improvement of Doubly Fed Induction Machine Functioning in Motor Mode by the DTC Control

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**ABSTRACT**

In this article, we are interested in the performances improvement of Doubly Fed Induction Machine (DFIM) operating in motor mode by the use of the direct torque control (DTC). Firstly, we focused on the modeling of the DFIM and the study of the functioning principle of the DTC control. Then, we implement this control on the Matlab/Simulink environment. Secondly, we present the simulation results of the proposed control. The analysis of these results shows clearly that the system based on the DFIM studied follows perfectly the set points, what allowed us to justify the efficiency of the elaborate control.



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## 1. INTRODUCTION

Currently, the doubly fed induction machine (DFIM) is widely used in high power industrial applications, due to many advantages over other rotating electrical machines [1]. The supply of the DFIM working in motor mode and in variable speed is assured by two inverters of voltage which are reciprocally connected to the stator and rotor windings [2]. The control of this machine, which is essentially non-linear due to the coupling between the flux and the electromagnetic torque, is relatively complex [3]. Several control strategies are used to control the DFIM to obtain a decoupling between the torque and the flux [4]-[5]. But, we always look by using innovative solutions of control to improve its performances.

The direct torque control (DTC) present an attractive solution to have a functioning with better performances of this machine, in the variable speed applications. This control strategy was introduced by Takahashi [6]-[7] and Depenbrock [8], it is mainly characterized by a good dynamic response of the torque, a good robustness and a lesser complexity with regard to other control.

In this work, we present the direct torque control of a DFIM functioning in motor mode. The objective is to guarantee the best performances regarding the robustness vis-a-vis the variations of its parameters and the load torque. The first part of this article will be devoted to the modeling of the DFIM. The

second part deals with the control of this machine. In a third part, in order to validate our model, simulation results using the Matlab/Simulink software will be presented and analyzed.

## 2. MODELING OF THE DFIM

The global system is illustrated in Figure 1 below, it consists of two converters, one is connected to the stator and the other is connected to the rotor of the machine studied [9]-[10].

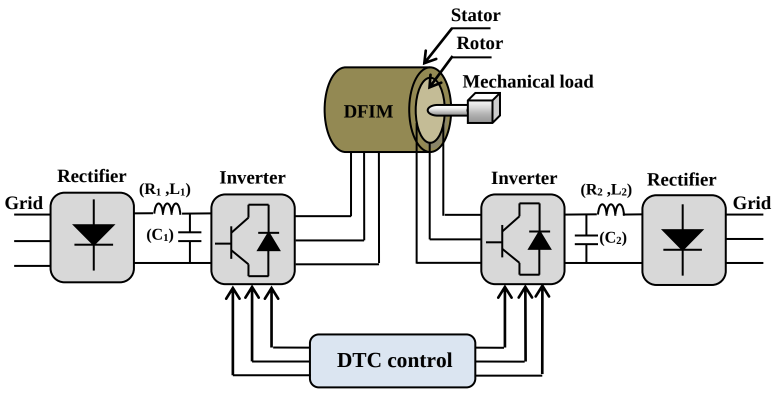


Figure1. Overall scheme of the system studied

The model of the doubly fed induction machine after the Park transformation is defined by the electrical, magnetic and mechanical following equations [11]-[12]:

### 2.1. The electrical equations

The electrical stator and rotor equations of the DFIM in the reference frame (d, q) are expressed by [13]-[14]:

$$\begin{cases} V_{sd} = R_s.i_{sd} + \frac{d\varphi_{sd}}{dt} - \frac{d\theta_s}{dt}.\varphi_{sq} \\ V_{sq} = R_s.i_{sq} + \frac{d\varphi_{sq}}{dt} + \frac{d\theta_s}{dt}.\varphi_{sd} \\ V_{rd} = R_r.i_{rd} + \frac{d\varphi_{rd}}{dt} - \frac{d\theta_r}{dt}.\varphi_{rq} \\ V_{rq} = R_r.i_{rq} + \frac{d\varphi_{rq}}{dt} + \frac{d\theta_r}{dt}.\varphi_{rd} \end{cases} \quad \text{with: } \omega_s = \frac{d\theta_s}{dt} = \frac{d\theta_r}{dt} + \frac{d\theta}{dt} \tag{1}$$

$$\begin{cases} i_{sd} = \frac{1}{\sigma L_s}.\varphi_{sd} - \frac{M}{\sigma L_r.L_s}.\varphi_{rd} \\ i_{sq} = \frac{1}{\sigma L_s}.\varphi_{sq} - \frac{M}{\sigma L_r.L_s}.\varphi_{rd} \\ i_{rd} = -\frac{M}{\sigma L_s.L_r}.\varphi_{sd} + \frac{1}{\sigma L_r}.\varphi_{rd} \\ i_{rq} = -\frac{M}{\sigma L_s.L_r}.\varphi_{sq} + \frac{1}{\sigma L_r}.\varphi_{rq} \end{cases} \quad \text{with: } \sigma = 1 - \frac{M}{L_s.L_r} \text{ and } M=M_{sr}=M_{rs} \tag{2}$$

### 2.2. The magnetic equations

The expressions of the flux are extracted from the electrical Equations (2):

$$\begin{cases} \varphi_{sd} = L_s.i_{sd} + M.i_{rd} \\ \varphi_{sq} = L_s.i_{sq} + M.i_{rq} \\ \varphi_{rd} = L_r.i_{rd} + M.i_{sd} \\ \varphi_{rq} = L_r.i_{rq} + M.i_{sq} \end{cases} \tag{3}$$

### 2.3. The mechanical equation

The fundamental equation of dynamics:

$$T_{em} = T_r + J.\frac{d\Omega}{dt} + f.\Omega \tag{4}$$

The electromagnetic torque is expressed as a function of the currents and the flux by:

$$T_{em} = p.\left(\varphi_{sd}.i_{sq} + \varphi_{sq}.i_{sd}\right) \quad (5)$$

With:

| | |
|---|---|
| $V_{s(d,q)}, V_{r(d,q)}$ | : Stator and rotor voltages in the reference frame (d, q). |
| $I_{s(d,q)}, I_{r(d,q)}$ | : Stator and rotor currents in the reference frame (d, q). |
| $\varphi_{s(d,q)}, \varphi_{r(d,q)}$ | : Stator and rotor flux in the reference frame (d, q). |
| $R_s, R_r$ | : Stator and rotor resistances. |
| $L_s, L_r$ | : Stator and rotor inductances. |
| $M$ | : Mutual inductance. |
| $P$ | : Pole pair number. |
| $\sigma$ | : Dispersion coefficient. |
| $\omega_s, \omega_r$ | : Stator and rotor pulsations. |
| $T_{em}, T_r$ | : Electromagnetic and load torque. |
| $\Omega$ | : Rotation speed of the machine (ω=p.Ω). |
| $J$ | : Moment of inertia. |
| $f$: | : Coefficient of viscous friction. |

The implementation on Matlab/Simulink of the DFIM is represented by the following Figure 2:

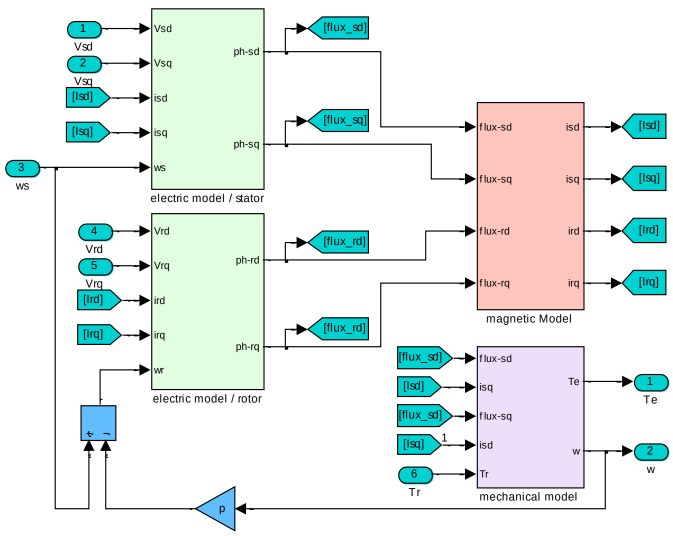


Figure 2. Simulink Model of the DFIM

## 3. DIRECT TORQUE CONTROL

### 3.1. Principle of the DTC control

The general principle of direct torque control is based on the direct regulation of the torque and flux of the doubly fed induction machine by selecting one of the eight voltage vectors generated by each voltage inverter. This choice is generally based on the use of hysteresis regulators whose function is to control the state of the machine [15]-[16]. The voltage vector *V* can be written in the form [17]:

$$V = \sqrt{\frac{2}{3}}U_0\left(S_a + S_b e^{\frac{j2\pi}{3}} + S_c e^{\frac{j4\pi}{3}}\right) \quad (6)$$

- $S_{i(i=a,b,c)}$=0 if the high switch is closed and the low switch is open.
- $S_{i(i=a,b,c)}$=1 if the high switch is open and the low switch is closed.

The combinations of three magnitudes ($S_a$, $S_b$, $S_c$) allow to generate eight positions of the voltage vector V which two correspond to the zero vector ($S_a$, $S_b$, $S_c$) = (000) and (111) as shown in Figure 3.

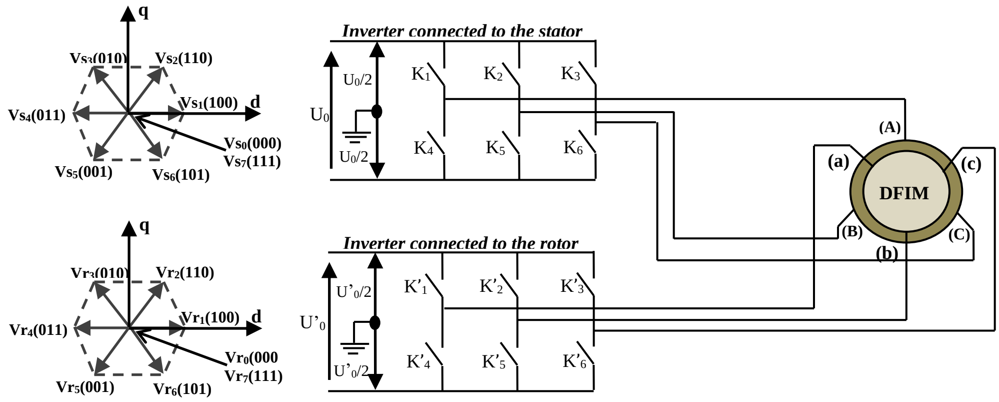


Figure 3. Elaboration of voltage vectors from voltage inverters of the DFIM

### 3.2. Strategy of the DTC control

To realize this command it is necessary every instant to control the stator flux, the rotor flux and the electromagnetic torque of the machine.

#### 3.2.1. Control of the stator and rotor flux

The relation between the flux vectors of the DFIM and the voltage vectors is given by the following equations system [18]:

$$\begin{cases} \overrightarrow{\phi_s}(t) = \int_0^t (\overrightarrow{V_s} - R_s\,.\overrightarrow{I_s}).dt + \vec{\phi}_{s0} \\ \overrightarrow{\phi_r}(t) = \int_0^t (\overrightarrow{V_r} - R_r\,.\overrightarrow{I_r}).dt + \vec{\phi}_{r0} \end{cases} \tag{7}$$

On an interval [0, $t_e$], we consider that the terms $R_sI_s$ and $R_rI_r$ are respectively negligible in front of Vs and $V_r$. Thus, we can write the equations (7) in the form:

$$\begin{cases} \overrightarrow{\phi_s} = \vec{\phi}_{s0} + \overrightarrow{V_s}.t_e \\ \overrightarrow{\phi_r} = \vec{\phi}_{r0} + \overrightarrow{V_r}.t_e \end{cases} \tag{8}$$

In general, for each flux we have:

$$\vec{\phi}_{(k+1)} = \vec{\phi}_{(k)} + \vec{V}.t_e \tag{9}$$

With:

$\vec{\phi}_{(k)}$ : Vector of the flux in the step of current sampling.
$\vec{\phi}_{(k+1)}$ : Vector of the flux in the step of following sampling.
$t_e$ : Sampling period.

In order to obtain a functioning with a module of constant flux, we can follow the extremity of $\vec{\phi}$ on an almost circular trajectory, by choosing a correct sequence of the vector V for the different successive time intervals of duration $t_e$.

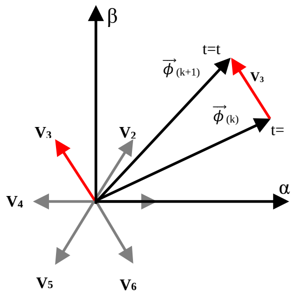


Figure 4. Example of the evolution of $\vec{\phi}$ extremity

### 3.2.2. Control of the electromagnetic torque

The expression of the electromagnetic torque in the reference frame (α, β) is written [19]:

$$T_{em} = \frac{3\, p\, M}{2\, \sigma L_s L_r} . |\vec{\phi}_r|.|\vec{\phi}_s|. sin(\delta) \tag{10}$$

With: $\delta = \theta_s - \theta_r$: the angle of phase shift between the two stator and rotor flux.

According to the equation (10), we notice that the electromagnetic torque of the DFIM depends on the amplitude of two vectors $\vec{\phi}_s$ and $\vec{\phi}_r$ and the angle between them, if we succeed in controlling perfectly this two flows in module and in position, we can thus control the torque.

### 3.2.3. Choice of the voltage vector

The voltage vector selection depends on the flux position in the reference frame (α, β) and the variation desired for the flux module and for the electromagnetic torque. The evolution space of the flux is decomposed into six sectors of 60 °: When the flux vector is in the sector $S_i$, the control of the flux and the torque can be made in the way presented in the following Table 1:

Table 1. Choice of the voltage vector

| The evolution of the flux and the torque | | Choice of the voltage vector |
|---|---|---|
| Flux | Torque | |
| Increasing | Increasing | $V_{i+1}$ |
| Decreasing | Increasing | $V_{i+2}$ |
| Increasing | Decreasing | $V_{i-1}$ |
| Decreasing | Decreasing | $V_{i-2}$ |

The vectors $V_0$ and $V_7$ are chosen to stop the movement of the flux.

## 3.3. Estimation of the flux and the torque

The estimation of the stator and rotor flux is basing of the stator and rotor voltages and currents. The flux components of the DFIM in the reference frame (α, β) are determined by [20]:

$$\begin{cases} \hat{\varphi}_{s\alpha} = \int_0^t (v_{s\alpha} - R_s . i_{s\alpha}). dt \\ \hat{\varphi}_{s\beta} = \int_0^t (v_{s\beta} - R_s . i_{s\beta}). dt \\ \hat{\varphi}_{r\alpha} = \int_0^t (v_{r\alpha} - R_r . i_{r\alpha}). dt \\ \hat{\varphi}_{r\beta} = \int_0^t (v_{r\beta} - R_r . i_{r\beta}). dt \end{cases} \tag{11}$$

With:$\overline{\phi}_s = \hat{\varphi}_{s\alpha} + j. \hat{\varphi}_{s\beta}$ and $\overline{\phi}_r = \hat{\varphi}_{r\alpha} + j. \hat{\varphi}_{r\beta}$. The modules of the stator and rotor flux are written:

$$\begin{cases} \hat{\phi}_s = \sqrt{\hat{\varphi}_{s\alpha}{}^2 + \hat{\varphi}_{s\beta}{}^2} \\ \hat{\phi}_r = \sqrt{\hat{\varphi}_{r\alpha}{}^2 + \hat{\varphi}_{r\beta}{}^2} \end{cases} \tag{12}$$

The positions of the flux vectors are calculated as follows:

$$\begin{cases} \theta_s = arctg\, (\frac{\hat{\varphi}_{s\beta}}{\hat{\varphi}_{s\alpha}}) \\ \theta_r = arctg\, (\frac{\hat{\varphi}_{r\beta}}{\hat{\varphi}_{r\alpha}}) \end{cases} \tag{13}$$

The electromagnetic torque is estimated from the measured stator currents:

$$\hat{T}_{em} = p. (\hat{\varphi}_{s\alpha}. i_{s\beta} - \hat{\varphi}_{s\beta}. i_{s\alpha}) \tag{14}$$

The DTC control is vectorial, it is necessary to decompose three currents and voltages ($i_{abc}$, $V_{abc}$) in components direct ($i_\alpha$, $V_\alpha$) and quadratic ($i_\beta$, $V_\beta$) according to the Concordia transformation, such as:

$$\begin{pmatrix} X_\alpha \\ X_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{pmatrix} \cdot \begin{pmatrix} X_a \\ X_b \\ X_c \end{pmatrix} \quad (15)$$

With: $X = V_s$, $V_r$, $i_s$ or $i_r$.

## 3.4. Elaboration of the control vector (Switching table)

### 3.4.1. Regulators elaboration of the flux and the torque

The difference $\varepsilon_\phi$, between the reference flux $\phi_{ref}$ and the estimated flux $\phi_{est}$ is introduced into a hysteresis regulator with two-level, the latter will generate the binary variable ($H_\phi$ = 0, 1) at its output, representing the desired evolution for the flux:

a. $H_\phi$=0 means that the flux must be decreased.

b. $H_\phi$=1 means that the flow must be increased.

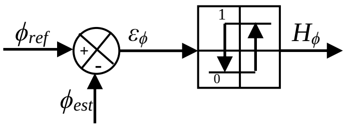


Figure 5. Hysteresis regulator with two levels

Similarly, the immediate error of the couple $\varepsilon_{Tem}$ is calculated by comparing its reference value $T_{em\text{-}ref}$ and its estimated value $T_{em\text{-}est}$, then applied to a three-level hysteresis regulator, generating at its output the variable $H_{Tem}$ with three levels (-1,0,1), representing the direction of temporal evolution desired for the torque:

a. $H_{Tem}$ = 1 means that the torque must be increased.

b. $H_{Tem}$ = 0 means that the torque must be decreased.

c. $H_{Tem}$=-1 means that it is necessary to maintain the torque inside the band.

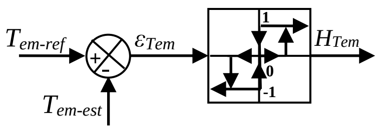


Figure 6. Hysteresis regulator with three levels

### 3.4.2. Elaboration of the switching table.

The state choice of each voltage inverter is made in a switching table elaborated according to the state of the variables ($H_\phi$ and $H_{Tem}$) at the output of the flux regulators and the electromagnetic torque, as well as sector giving the information about the position of vector of the flux. Table 2 is presented in the following form:

Table 2. Switching table

| | | Sector $S_i$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| $H_{\phi s}$ or $H_{\phi r}$ | $H_{Tem}$ | voltage vector | | | | | |
| 1 | 1 | $V_2$(110) | $V_3$(010) | $V_4$(011) | $V_5$(001) | $V_6$(101) | $V_1$(100) |
| 1 | 0 | $V_7$(111) | $V_0$(000) | $V_7$(111) | $V_0$(000) | $V_7$(111) | $V_0$(000) |
| 1 | -1 | $V_6$(101) | $V_1$(100) | $V_2$(110) | $V_3$(010) | $V_4$(011) | $V_5$(001) |
| 0 | 1 | $V_3$(010) | $V_4$(011) | $V_5$(001) | $V_6$(101) | $V_1$(100) | $V_2$(110) |
| 0 | 0 | $V_0$(000) | $V_7$(111) | $V_0$(000) | $V_7$(111) | $V_0$(000) | $V_7$(111) |
| 0 | -1 | $V_5$(001) | $V_6$(101) | $V_1$(100) | $V_2$(110) | $V_3$(010) | $V_4$(011) |

The general structure of direct torque control of the doubly fed induction machine is detailed in the following Figure 7:

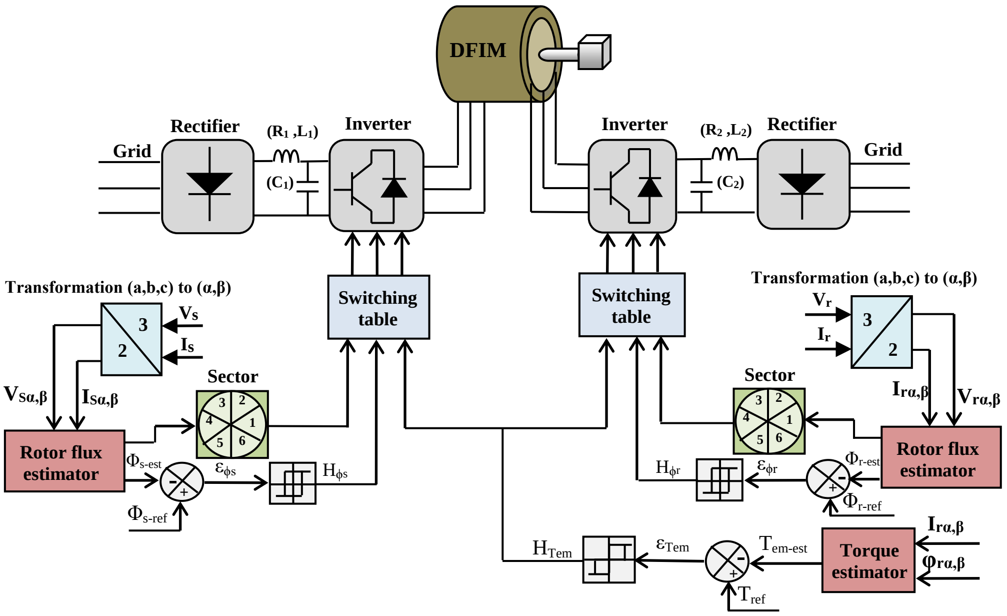


Figure 7. General structure of the direct torque control applied to the DFIM

## 4. RESULTS AND DISCUSSION

The global model of the system studied (DFIM and blocks of the DTC control) is simulated in the Matlab/Simulink environment.

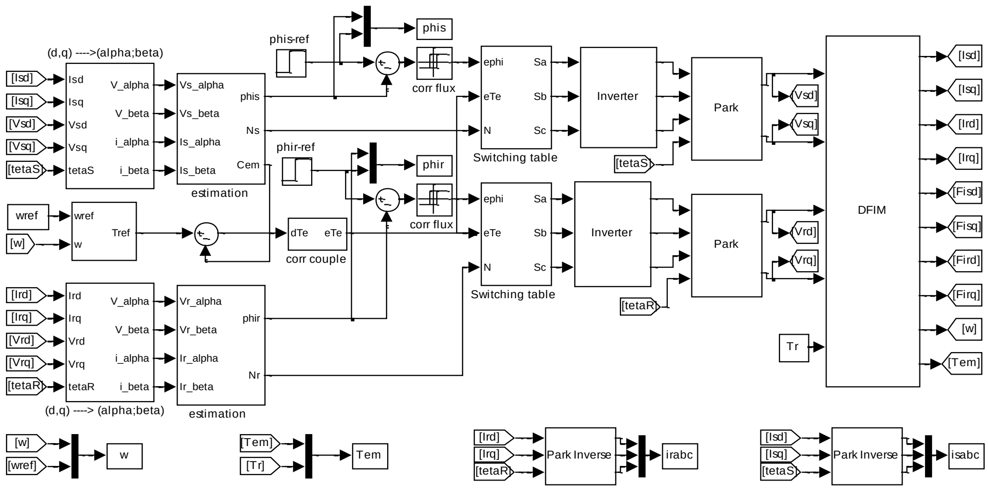


Figure 8. Simulation scheme of the DTC control on the Matlab/Simulink environment

### 4.1. Simulation results

To show the performances of direct torque control applied to DFIM, we present the simulation results of the system for reference flux ($\phi_{s\text{-}ref}$ = 1Wb, $\phi_{r\text{-}ref}$ = 0.5Wb). The bandwidth of hysteresis comparator of the torque is fixed in ±0.01N.m and those of the comparators of the stator and rotor flows are fixed to ±0.005 Wb.

#### 4.1.1. Test with constant speed

The figures below present the response of the magnitudes of the doubly fed induction machine at constant speed and variable load (the reference torque of set-points ranging from 0 → 10 N.m → 5 N.m). In this test, the rotation speed reaches its reference without overtaking, it is insensitive to changes in the load (Figure 9.a). Figure 9.b show that the torque has good dynamics whose mean value follows the setpoint values with a very fast response time which equals $t_r$ = 0.32s, but it has low ripples. The stator and rotor flux remain constant at its reference values whatever the applied load which shows that the torque and the flux are decoupled (Figure 9.c). The evolution of these flows in the reference frame (α, β) is perfectly circular (Figure 9.d). The components of the stator and rotor currents in the (a, b, c) reference have sinusoidal patterns with a frequency proportional to the reference speed, they reply well to the variations imposed by the load torque (Figure 9.e and Figure 9.f).

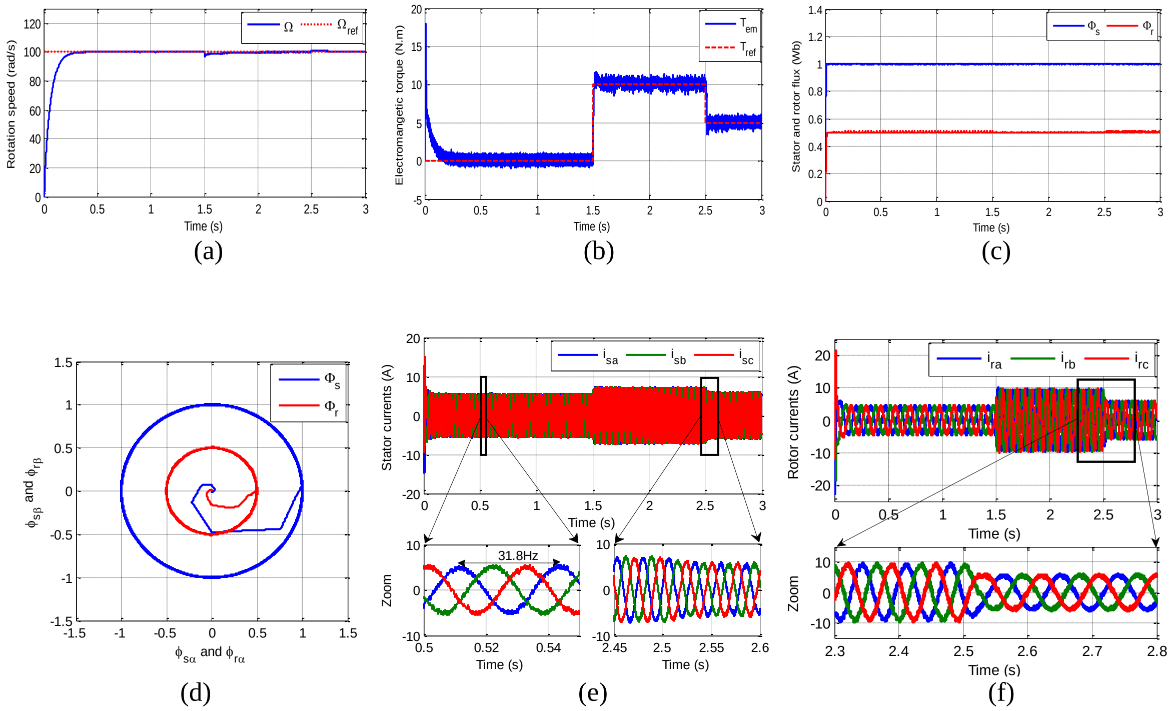


Figure 9. Test with constant speed, (a) Rotation speed (b) Electromagnetic torque (c) Stator and rotor flux (d) Evolution of the stator and rotor flux in the reference frame (α, β) (e) Stator currents (f) Rotor currents

#### 4.1.2. Test with variable speed

The figures below show the simulation results of the DTC control applied to DFIM with variable speed and variable load. In the variable speed test, the Figure 10.a and Figure 10.b show the high dynamics of the rotation speed and the electromagnetic torque of the DFIM, with a fast response time to the change of the set-points. The components of the stator and rotor currents in the (a, b, c) reference are always sinusoids, their frequencies and their amplitudes vary respectively as a function of the rotation speed and the load torque imposed (Figure 10.e and Figure 10.f). The stator and rotor flux remain constant at its reference values, which validates that the DTC control is robust towards the variation of the load and the speed as shown in Figure 10.c. These stator and rotor flux are trapped in a circle regardless of the applied load, which shows that the flux constancy despite the load as shown in Figure10.d, we conclude that the torque and flux are decoupled. These simulation results show the effectiveness of this control technique.

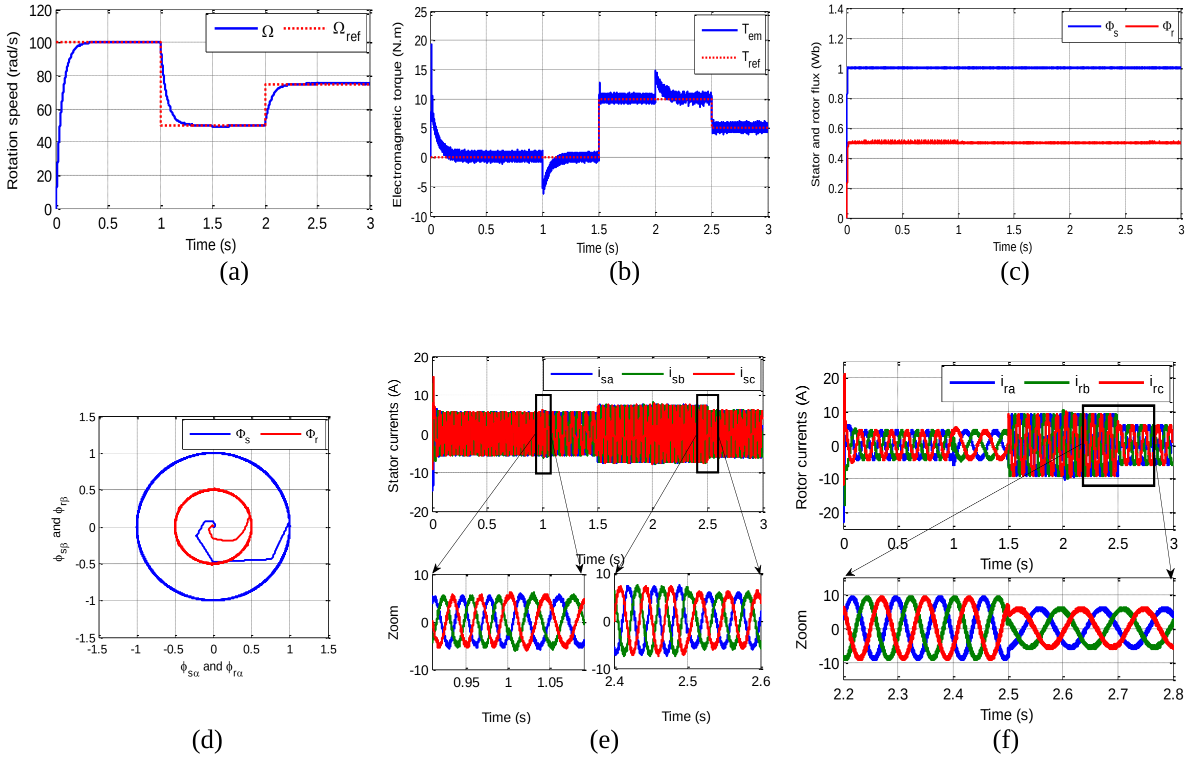


Figure 10. Test with variable speed, (a) Rotation speed (b) Electromagnetic torque (c) Stator and rotor flux (d) Evolution of the stator and rotor flux in the reference frame (α, β) (e) Stator currents (f) Rotor currents

## 5. CONCLUSION

In this work, we presented the direct torque control applied to a DFIM used in motor mode, powered by two converters, one on the stator and the other on the rotor. After a study of the modeling of the system, we realized the implementation of the DTC control based on the direct regulation of flux and torque. The interpretation of the obtained results shows clearly that the system follows perfectly the reference values and, by consequence, supplies a good static and dynamic performance of the studied machine.

## APPENDIX

Table 3. Parameters of the DFIM

| Variable | Symbol | Value (unit) |
|---|---|---|
| Nominal power | $P_m$ | 1.5 kW |
| Stator nominal voltage | $V_{sn}$ | 220V |
| Rototor nominal voltage | $V_{rn}$ | 130V |
| Frequency | f | 50 Hz |
| Pair pole number | P | 2 |
| Stator self inductance | Ls | 0.295 H |
| Rotor self inductance | Lr | 0.104 H |
| Maximum of mutual inductance | M | 0.165 H |
| Stator resistance | $R_s$ | 1.75 Ω |
| Rotor resistance | $R_r$ | 1.68 Ω |
| Total viscous frictions | f | 0.0027 Kg.m²/s |
| Total inertia | J | 0.01 Kg.m² |

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